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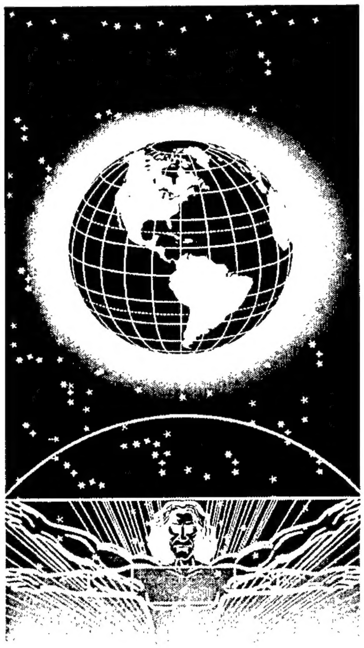

UNITED STATES AIR FORCE RESEARCH LABORATORY

Flow Stagnation as an Advanced Windblast Protection Technique

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June 2002

Final Report for the Period April 1982 to September 1985

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REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
June 2002	Final	April 1982 to September 1985

4. TITLE AND SUBTITLE Flow Stagnation as an Advanced Windblast Protection Technique	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 62202F
6. AUTHOR(S) Lawrence J. Specker	**5d. PROJECT NUMBER** 7184
	5e. TASK NUMBER 31
	5f. WORK UNIT NUMBER 04
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Human Effectiveness Directorate Biodynamics and Protection Division Biodynamics and Acceleration Branch 2800 Q Street Wright-Patterson AFB OH 45433-7947	**10. SPONSOR/MONITOR'S ACRONYM(S)** AFRL/HEPA **11. SPONSOR/MONITOR'S REPORT NUMBER(S)** AFRL/HE-WP-TR-2002-0143

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
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15. SUBJECT TERMS
Windblast protection, flow-stagnation, ejection seat, escape system

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Lawrence J. Specker
UC	UC	UC	UL	6	**19b. TELEPHONE NUMBER** *(Include area code)* (937) 255-3931

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

NOTICES

TECHNICAL REVIEW AND APPROVAL

AFRL-HE-WP-TR-2002-0143

This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

FOR THE DIRECTOR

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FLOW STAGNATION AS AN ADVANCED WINDBLAST PROTECTION TECHNIQUE

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ABSTRACT. A windblast protection device which uses high-strength, deployable fabric panels has been tested. The panels capture and slow the aerodynamic flow impinging on the ejection seat occupant's extremities and torso and reduce the probability of injury caused by windblast. Wind tunnel tests were conducted in low- and high-speed wind tunnels using one-half scale models of a fiftieth-percentile size male crewmember and ejection seat. Measurements taken included forces and moments acting on the crewmember's arms, legs, and head; total forces and moments on the crewmember and seat model; and static pressure on the surface of the crewmember and flow-stagnation panels. Additional tests were accomplished to measure full-scale static aerodynamic coefficients of various flow-stagnation panel configurations. These tests were accomplished with volunteer subjects and a modified ejection seat. This paper reviews the current tests accomplished using the flow-stagnation concept as well as tests utilizing the concept 25 and 45 years ago. Successful application of the flow-stagnation concept is a promising candidate solution to the problem of windblast protection.

INTRODUCTION. The performance capability of emergency ejection seats is limited at high speeds by the occurrance of windblast injuries rather than by the maximum qualification test speed that is commonly cited. Serious windblast injuries may occur at relatively low airspeeds. For example, the U.S. Air Force non-combat injury rate due to aerodynamic forces exceeds 10% at 375 knots. At 500 knots, the major and fatal injury rate increases to nearly 50%.[1] The injuries range from joint dislocation and long bone fracture to cervical cord transection. If the injuries are survivable, long recovery periods are frequently required, and in cases where there is joint disruption or nerve involvement, return to flight status may not be possible.

Conventional approaches to windblast protection have used extremity restraints, such as leg garters and arm sleeves which must be donned and attached to the seat by encumbering straps. Head and neck protection concepts have restricted head and neck mobility, added bulk, presented actuation problems, and frequently have created added injury hazards. Therefore, conventional windblast protection systems have not been readily accepted.

BACKGROUND. Physical processes which produce windblast injuries are relatively well understood. There is great disparity between the forces acting on the extremities of an ejectee and those acting on the seat during ejection into a high-velocity windstream. The limbs are forced outward and backward due to the direction of the aerodynamic flow and because of their higher drag characteristics they decelerate more rapidly than the torso and seat. If the arms and legs are dislodged from the seat by the aerodynamic and inertial forces and if the airspeed is sufficiently high, the extremities are injured when joint strength is exceeded or when the long bones are fractured by contact with the seat structure. Injury of the cervical spine is caused by tension, bending, and/or shear loads resulting from inequalities of the aerodynamic forces and accelerations acting on the head and neck.

The apparent general solutions are to restrain all extremities to the seat or to reduce the disparities between the forces acting on the limbs by altering the aerodynamic flow and inertial loads. However, implementation of these solutions is difficult in the face of numerous design constraints imposed by the seat occupant, the aircraft, and other escape system design requirements. Such constraints effectively eliminate schemes such as total body restraint or heavy mechanisms that protrude in front of the seat to deflect the aerodynamic flow away from the seat occupant.

State-of-the-art ejection seat stabilization is also a major factor that constrains the design of an effective windblast protection system. Wind tunnel test data and the results of rocket sled tests demonstrate that ejection seats have not achieved adequate directional stability at high-speed. This problem has severely compromised the effectiveness of side panels and nets which are intended to prevent extremity flail injuries. However, directional control has been improved in the recent generation of ejection seats and further advancements are anticipated in the next decade. Therefore, protection schemes predicated upon seat stabilization may prove to have merit as longer term solutions.

NEW APPLICATION OF PROVEN APPROACH. One of the most promising approaches to provide windblast protection for stabilized, open ejection seats is the flow-stagnation concept proposed by Cummings[2] (Figure 1). The principle of the concept is to trap a volume of air in front of and around the seat occupant. The trapped air equalizes the pressures around the torso and limb segments and eliminates the net aerodynamic load that normally pulls the limbs out of their stowed positions and into the

FIGURE 1. FLOW-STAGNATION CONCEPT PROPOSED BY CUMMINGS.

freestream. The stagnated flow provides "aerodynamic encapsulation" diverting the high-velocity airflow around the seat occupant. The design configuration being studied uses fabric panels erected around the seat-occupant's head, torso, and upper legs prior to entry into the windstream. As conceived, the panels would be stored on the sides of the seat over the headrest. The panels could be deployed either by powered reels or by seat motion during ejection from the cockpit.

The concept of using flow-stagnation for protection from high-pressure flow is not new. Schütze, in 1941, reported experiments carried out for the German Air Force on the effect of high airspeed on the face with and without protection.[3] The research was carried out by flying in an open cockpit aircraft from which the windshield had been removed, and it was found that the eyelids of cockpit occupants tended to be forced open at about 270 knots. Schütze also found the severity of the effects on the face could be reduced if a flat plate was placed behind the head. The plate was described as a headrest varying in width from 2-3 times the size of the head. These headrests stopped the airflow in the area of the head, "diverted the blast" and allowed the subject to keep the eyes open at 270 knots.

Fryer, in 1961, conducted underwater centrifuge tests to study the effects of dynamic pressure on the human body. Considerable effort was taken to provide restraint for the human subjects. Head restraint, particularly against severe oscillations, was thought to be one of the major developments necessary to extend seat performance limits. Reduction of flow in the head area was accomplished by placing the head of the subject in a cowl, fitting snugly over the shoulders, close to the sides of the head and closed at the rear. A picture of the cowl is shown in Figure 2. The legs were strapped at the thighs and ankles, and the arms were held in steel channels by retaining cords in addition to the standard aircraft restraint. Multiple exposures to approximately 700 psf were accomplished with little difficulty. The maximum dynamic pressure achieved was 1040 psf. Adverse but temporary effects experienced by the subjects included significant bruising at the shoulder and groin, hip pain, and leg tenderness.

FIGURE 2. COWLING USED BY FRYER IN UNDERWATER CENTRIFUGE TESTS.

The studies of Schütze and Fryer demonstrate the feasibility of reducing the flow in the region of the head and increasing subjects' tolerability to high dynamic pressure flow. But applying the principle to ejection seat design might require the solution of basic aeromechanical problems. Schütze's experimental design and Cumming's proposal show a potential for increased system drag and exaggerated instability in the pitch and yaw axes.

SCALE-MODEL WIND TUNNEL TESTS. The effectiveness of the flow-stagnation concept proposed by Cummings and its influence on seat performance has been evaluated by wind-tunnel tests using the one-half-scale model of a crewmember and ejection seat shown in Figure 3.[6,7] The data

collected during the wind-tunnel tests indicated that the flow-stagnation panels are very effective at limiting the airflow within the cavity and at reducing the aerodynamic loads on the crewman's limbs. The pressure measured on and around the crewmember within the flow-stagnation panels showed the degree of stagnation ranged from 80 to 100 percent at low angles of attack (near -20 degrees). At high angles of attack (near +30 degrees) the pressures measured near the hips, head, and shoulders were greatly reduced indicating the degree of stagnation to be approximately 65 percent. The stagnation pressure also decreased with increasing sideslip angle from 90 percent at zero degree sideslip to 60 percent at 60 degrees sideslip.

FIGURE 3. CREWMAN AND SEAT MODEL WITH SMALL FLOW-STAGNATION PANELS.

The aerodynamic loads acting on the limbs showed significant reductions when the flow-stagnation panels were used. For example, the vertical forces on the head were lowered to nearly zero over the range of pitch angles tested as shown in Figure 4. The axial forces on the head were near zero with medium sized panels (3-in protrusion from seatback) to negative values with larger panels. The sideward forces on the head and arms were also reduced. The presence of the flow-stagnation panels affected the vertical force on the lower arms in the same manner as they did the axial forces on the head.

Mach number also has a significant effect on the aerodynamic forces acting on all the limb segments of the basic model. The limb forces generally increased with increasing Mach

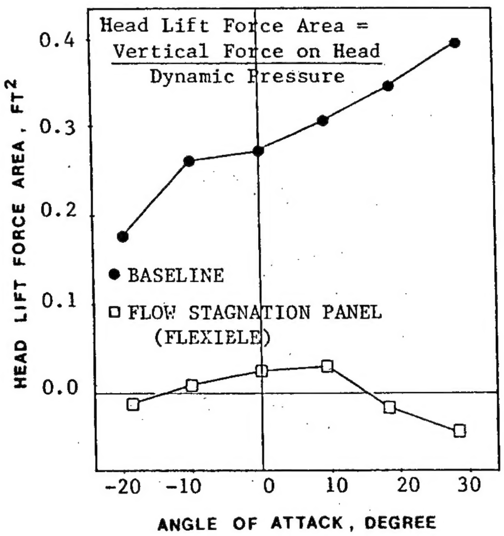

FIGURE 4. HEAD LIFT FORCE AREA VS. ANGLE OF ATTACK.

number. However, when the flow-stagnation panels were added, the limb forces were reduced again to nearly zero. Although the lift values for the head increased slightly with increasing Mach number, the values remained low in magnitude. The protection afforded by the flow-stagnation panels was effective for all limbs up to speeds of Mach 1.2.

Several significant seat performance characteristics indicated by the static aerodynamic coefficients were revealed when the flow-stagnation panels were added to the model. First, the axial force increased significantly with all flow-stagnation panel sizes tested. This increase ranged from 100 percent with the largest size panel to 75 percent with the smallest. Second, the magnitude of the pitching moment coefficient was reduced. This is due to the increase in the axial force on the upper portion of the seat model with the flow-stagnation panels. Third, the yawing moment coefficient and the side force coefficient were not changed with the addition of the flow-stagnation panels (Figure 5). And fourth, Mach number increased the total seat loads measured with and without the flow-stagnation panels and the low-speed data trends remained the same.

The crewman/seat model was not believed to be a reasonable indicator of seat performance characteristics with the flow-stagnation panels attached. Since the crewman's limbs were extensively instrumented, the flow-stagnation panels were purposely built outboard of the arms so that there was no possibility of interference. Interference between the flow-stagnation panel and limb would have altered the measurement or would have made the measurement impossible.

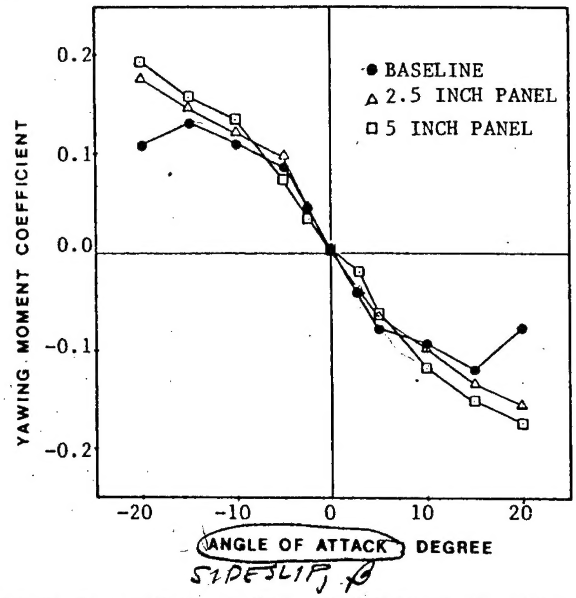

FIGURE 5. YAWING MOMENT COEFFICIENT VS ANGLE OF ATTACK.

The mounting structure for the flow-stagnation panels was reasoned to increase total seat drag and normal forces because of the increased projected frontal area. These increased loads would tend to increase already high deceleration loads and sink rates. A larger catapult and rocket motor would be required to compensate for these effects. The weight and volume requirements for the increased propellants in the escape system would preclude the use of the flow-stagnation panels.

FULL-SCALE WIND TUNNEL TESTS. To circumvent the difficulties of using instrumented scale models to evaluate the effects of the flow-stagnation panels on seat performance, full-scale tests were conducted. Prototypes of the flow-stagnation panels were fabricated and attached to an ejection seat. A total of seven flow-stagnation configurations were tested during two wind tunnel test series.[8,9] Human subjects were used during the test program and were outfitted with minimal flight gear. This consisted of a flight suit, an integrated parachute harness (PCU-15/P) and flight helmet (HGU-26/P), oxygen mask, and boots.

The full-scale static aerodynamic coefficients that were found with a flow-stagnation configuration that was similar to the one tested on the scale model indicated significant improvement. For example, the total seat drag was 40 percent greater than the drag measured for the baseline. The same measurement for the model indicated a 100% increase. The normal force coefficient showed a positive increment over the baseline configuration. The remaining aerodynamic coefficients reflected the trends observed in the scale-model wind tunnel tests.

Several of the full-scale configurations tested were designed to shift the point of airflow separation aft of the leading edge of the flow-stagnation panels. Principles of thrust vectoring were used to locate vent locations along the flow-stagnation panel. The venting allowed the high-pressure airflow from within the stagnation volume to enter the separated region along the side of the seat, re-energize the boundary layer, and delay flow separation.[10,11,12] The total drag of the crewmember and seat combination was significantly reduced for these configurations. Improvements of 14 to 26 percent in total drag were measured for the subject group. Drag or axial force coefficient values for various panel configurations are shown in Figure 6. The flow-stagnation panels with venting locations at the leading edge, two-thirds chord, and rear of the seat are shown in Figure 7.

DISCUSSION. Flow-stagnation is a basic principle in the study of fluid motion. Investigators used it for protection against high-dynamic pressure windblast 45 years ago, but the design was impractical and never adopted for operational use. Fryer showed considerable insight and successfully used the flow-stagnation principle to protect the head from oscillatory forces, but the principle was not then applied to ejection seat design. Cumming's proposal was timely because of advances in seat stabilization techniques and higher demands for improved escape system performance that required radical improvement in state-of-the-art windblast protection capability.

The scale-model wind tunnel tests demonstrated the effectiveness of the flow-stagnation panels

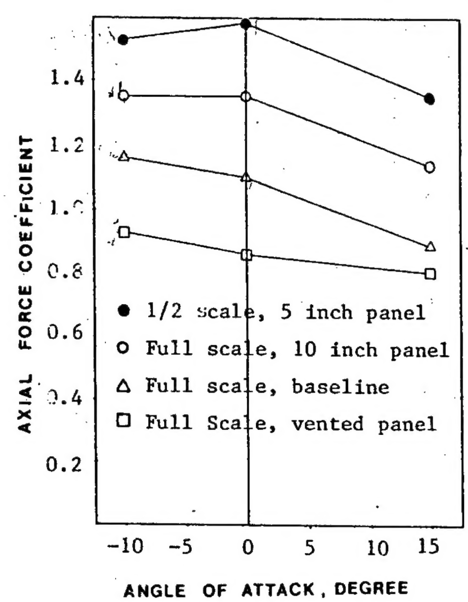

FIGURE 6. AXIAL FORCE COEFFICIENT VS ANGLE OF ATTACK.

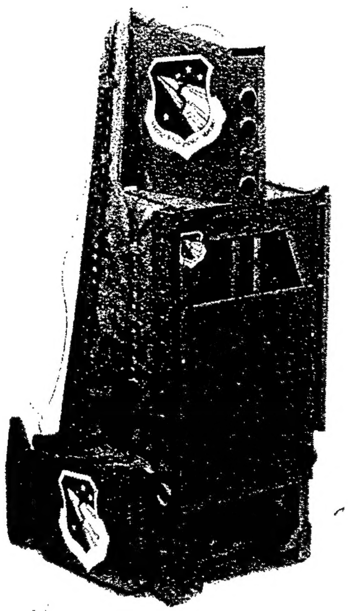

FIGURE 7. FLOW-STAGNATION PANELS WITH THREE VENT LOCATIONS.

in reducing the aerodynamic loading of the individual limb segments. However, the effectiveness was influenced by seat attitude. Increasing the pitch angle allowed the airflow to circulate around the crewmember and exit in the vicinity of the headrest. The result was usually an increase in vertical force on the head. Increasing the yaw angle beyond 20 degrees also reduced the protective effect of the flow-stagnation panel. Beyond 20 degrees of yaw the flow-stagnation panel collapsed. Reinflation of the panels would usually not occur until the seat returned to yaw angles of 10 degrees.

The design configuration of the full-scale panels is critical to seat performance. The panels can be designed to enhance the aerodynamic characteristics of the basic ejection seat design using techniques that are recognized in more conventional aerodynamic application. Boundary-layer control using thrust vectoring and blowing are useful in low- and high-speed flow. When these principles are combined with tight-fitting flow-stagnation panels, the total drag penalty of the crewmember and seat combination can be significantly reduced. Venting of the seat, however, reduces the degree of flow-stagnation occurring within the panels at low speeds and the degree of protection is also reduced. Optimization of the mass-flow rate of the air allowed to vent could be controlled with proper sizing of the vents to allow complete flow stagnation above speeds that pose significant threats to the ejecting crewmember. Below that speed the flow-stagnation panels would be less effective as stagnation devices.

CONCLUSIONS. The flow-stagnation windblast protection concept has been demonstrated to be a simple and effective means of protecting the crewmember at high windstream velocities. Low-speed wind tunnel tests have shown that aerodynamic improvements can be made to the crewmember and seat combination incorporating the flow-stagnation panels. However, additional testing is required to determine what effects the aircraft fuselage might have on an ejection seat equipped with flow-stagnation panels. Dynamic aerodynamic stability must also be addressed to allow control system and propulsion systems to be designed that can keep the seat attitude aligned properly into the windstream.

The U.S. Air Force is currently conducting an advanced development program called the Crew Escape Technologies (CREST) Advanced Development Program. The objective of the CREST program is to develop and demonstrate, through full-scale testing, new escape technologies required to reduce fatalities and major injuries in future aircraft ejections. Extending the high-speed performance limits to 700 KEAS is a major goal of the program. The flow-stagnation windblast protection technique is the leading candidate for windblast protection in the pursuit of this goal.

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BIOGRAPHY. Lawrence J. Specker is an Aerospace Engineer with the Biomechanical Protection Branch, Biodynamics and Bioengineering Division of the Harry G. Armstrong Aerospace Medical Research Laboratory. He has been involved in escape system research since his graduation from the University of Cincinnati in 1973. His research projects have included the investigation of powered pre-ejection body retraction systems, development of techniques to assess the effects of aircraft canopy birdstrike, design and development of several windblast protection systems, and studies of the aerodynamics of ejection seats and the human body.